Short Comments:

This comment was prepared through a group discussion of the SPATIAL laboratory at the University of Utah.

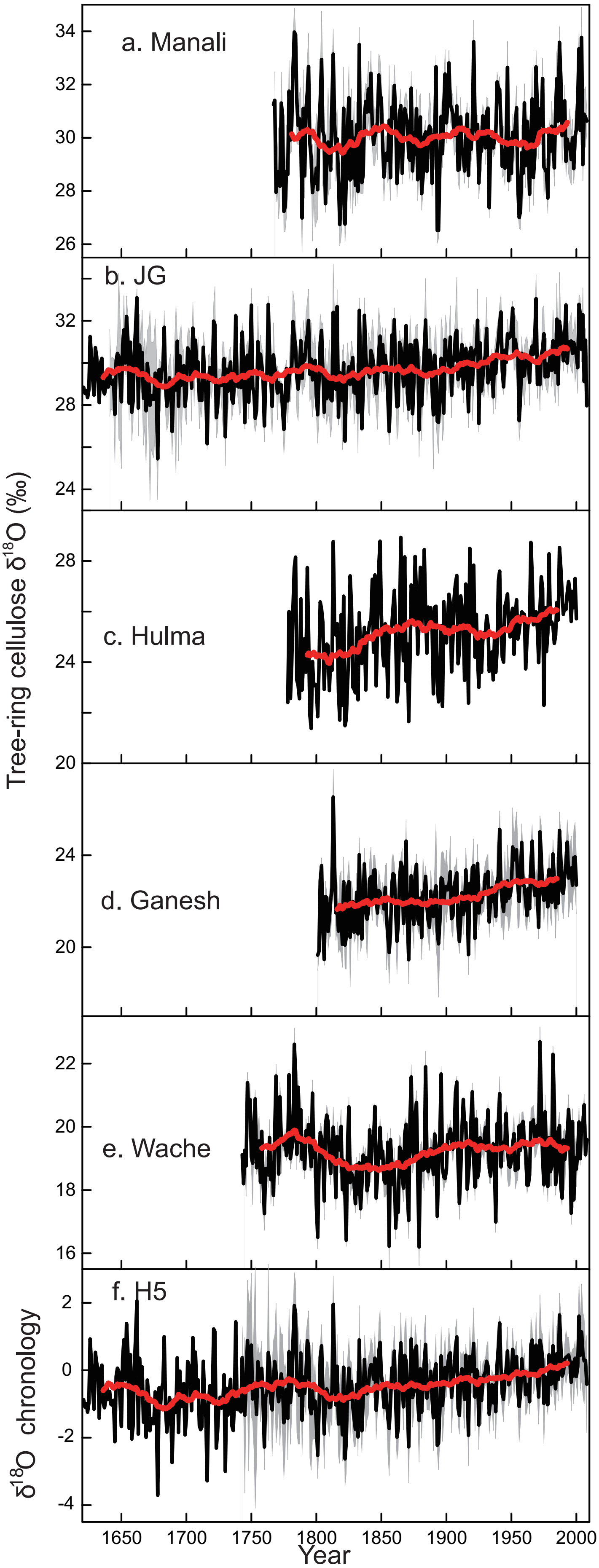
Overview: Xu et al. provide a new stacked record of tree ring cellulose oxygen isotopes from five locations along the southern Himalaya, spanning a time range of 1743-2008 CE. They find significant correlations with regional climate indices of precipitation and Indian monsoon strength over the instrumental record, and from this, infer that their stacked record can be used to reconstruct the strength of the Indian monsoon prior to the industrial record. From this, they draw two potentially exciting conclusions from their analysis: (a) high-frequency ENSO variability (e.g., periods of 2.4-5 years in their figure 7) may be recorded in the stacked tree ring dataset and (b) low-frequency centennial scale variability (e.g., periods of 160-350 years in their figure 7) may reflect long-term variability in monsoon strength, which they support by an analysis of long-term changes in the land-sea temperature contrast derived from proxy records. However, the authors do not provide information on uncertainty and error, and therefore, it is difficult to assess the robustness of their conclusions. Our view is that this data merits publication, but that considerable revisions need to be made to help clarify their analyses and support their conclusions. Therefore, we recommend acceptance pending major revisions described below.

Major comments:

(1) Error and uncertainty are not adequately explored or explained.

We provide several examples of analyses in the paper that would benefit from a more thorough treatment of error and uncertainty propagation: No uncertainty is given on the individual chronologies provided (e.g., the uncertainty from combining individual trees at a location to estimate the average delta18O record at that location), nor is it propagated to the averaged delta18O chronology of the stacked record in figure 4. The authors make several comparisons between their stacked tree ring record and other proxy indicators of ENSO (Fig. 9), stalagmite oxygen isotopes (Fig 10), and Indian Ocean SSTs and Tibetan Plateau temperatures (Fig 11). However, they do not consider either the potential errors in proxy reconstructed values (e.g., the error in reconstructed SSTs), nor potential errors in the age model used to assign a date to those proxy values. As a result, it is difficult to assess how robust the signals they derive from comparisons between proxy records are, and how they compare to the variability. For example, in figure 11, it is not clear that the reconstructed land-sea temperature anomaly is a substantial, robust, or significant deviation from zero if estimates of uncertainty are absent.

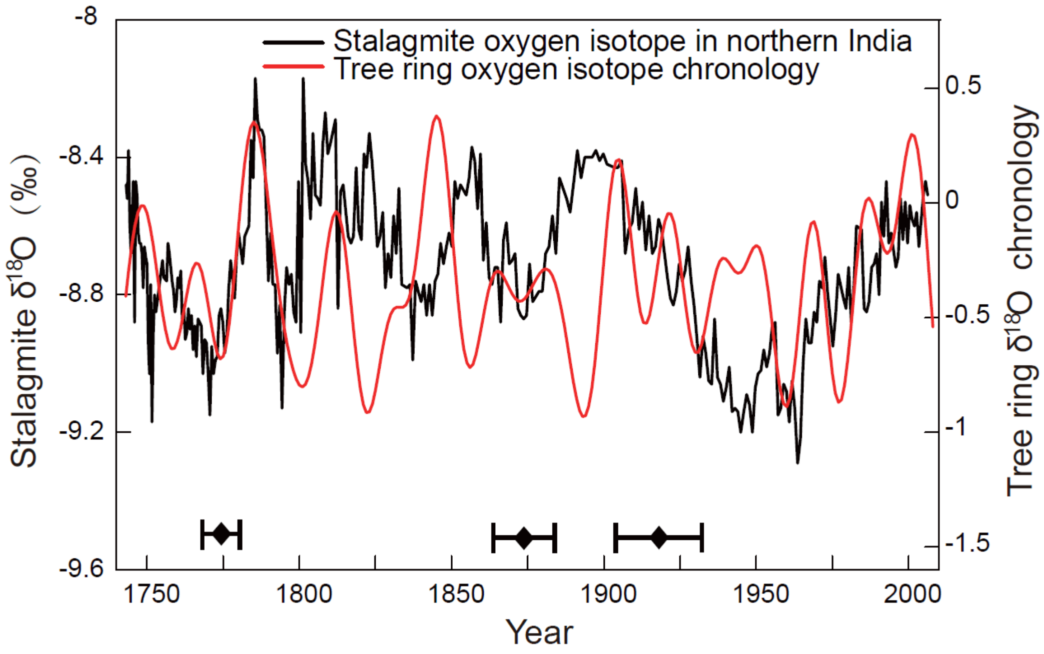
Answer: Thanks for your suggestions. We have added the 95% (±1.96σ) confidence limits of different tree ring oxygen isotope time series in Manali, JG, Ganesh and Wache as the uncertainty of inter-tree variability, which are shown in New Figure 4a,b,d,e in revised manuscript by gray shadows. For tree ring oxygen isotopes data in Hulma, we cannot evaluate the inter-tree oxygen isotope variability, because tree ring oxygen isotope chronology in Hulma was built up by pooling method. The uncertainty of regional tree ring oxygen isotope chronology was evaluated by showing the 95% (±1.96σ) confidence limits (Figure 4f). Please see the revised Figure 4.



a. Manali
b. JG
c. Hulma
d. Ganesh
e. Wache
f. H5
Tree-ring cellulose δ18O (‰)
δ18O chronology
Year
1650
1700
1750
1800
1850
1900
1950
2000

Figure Caption: Figure 4: Tree ring oxygen isotope chronologies from five sites (a-e) and the regional tree ring oxygen isotope chronology (f). (black line: mean values for all samples; red line: 31-year running average for the chronology; gray shadows: the 95% (±1.96σ) confidence limits)

For the uncertainty of age model for stalagmite oxygen isotope time series, we have added the dating results and uncertainty of stalagmite oxygen isotope data in northern India in new Figure 11. During the common period (1743-2000) between regional tree ring oxygen isotope chronology and stalagmite oxygen isotope data, there are three dating point with uncertainty in range of 9~31 years.



New Figure 11. Comparison between multi-decadal regional tree ring $\delta^{18}O$ variations (red line) with stalagmite $\delta^{18}O$ changes (black line) in northern India. Rhombus with error indicates the ^{230}Th dates with uncertainty in stalagmite $\delta^{18}O$ chronology.

To check robustness of the low-frequency land-sea temperature anomaly, three different temperature reconstruction (Cook et al., 2013; Shi et al., 2015; Wang et al., 2015) in Tibetan Plateau and one Indian Ocean SST reconstruction was used. Three land-see temperature anomaly time series showed similar lower frequency variations. A decreasing trend of land-sea temperature anomaly during the last 200 years were shown by three land-see temperature anomaly time series. In addition, we added the ± 1 RMSE (root mean square error) as uncertainties of each temperature reconstruction in Tibetan Plateau and Indian Ocean. The uncertainty of land-see temperature anomaly was calculating by adding RMSE from land and sea temperature reconstruction, which was shown by shadows in New Figure 10 in the revised manuscript.

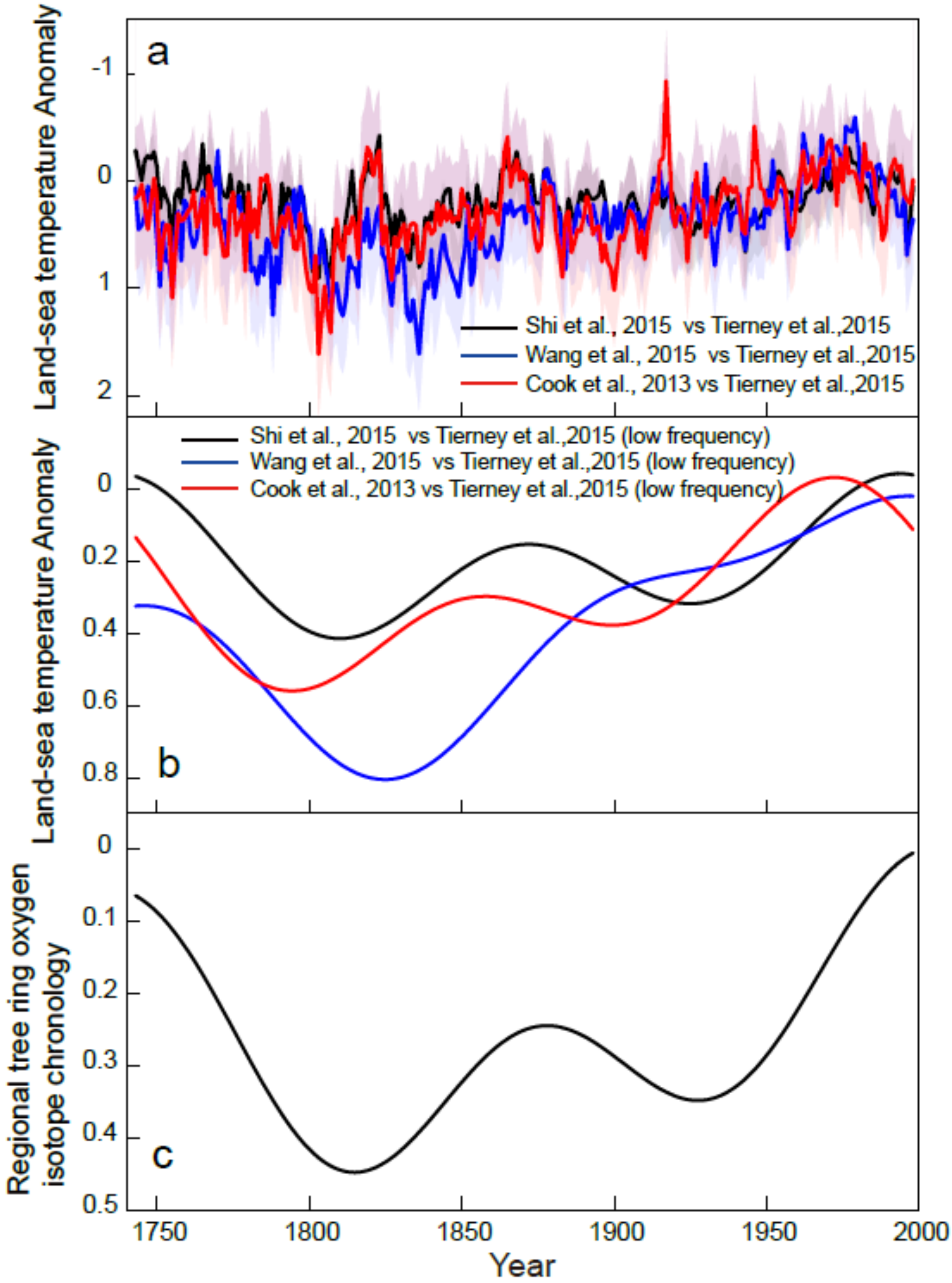


Figure Caption: Figure 10. a: Land-sea Temperature Anomaly based on three summer temperature reconstruction for the Tibetan Plateau and one Indian Ocean SST reconstruction;

b and c: centennial variations of land-sea thermal contrasts and the H5 regional tree ring $\delta^{18}O$ chronology.

(At the end of Section 3.5 of the revised manuscript)

Several studies show that increased Indian Ocean SSTs caused a reduction in ISM rainfall (Fan et al., 2009; Naidu et al., 2009; Sun et al., 2016). The Indian Ocean SST has increased since 1840-1860 CE (Tierney et al., 2015; Wilson et al., 2006), which supports this explanation. Although the SST of the Indian Ocean significantly affects the ISM, the land-sea thermal contrast is also an important influencing factor (Roxy et al., 2015). In particular, heating anomalies over the Tibetan Plateau have a significant influence on the ISM via their effect on the atmospheric temperature gradient between the Tibetan Plateau and the tropical Indian Ocean (Fu and Fletcher, 1985; Sun et al., 2010). The history of land-sea thermal contrasts is reconstructed based on temperature differences between the Tibetan Plateau and the Indian Ocean (Figure 10a), and centennial variations in this record are shown in Figure 10b. Three reconstructed land-sea thermal contrasts showed a decreasing trend since 1800 CE and 1820 CE (Figure 10b), and the H5 record exhibits a similar pattern of changes on a centennial scale (Figure 10c). The decreasing land-sea thermal contrast since 1800 and 1820 CE has resulted in a weaker ISM, and the increasing trend of the H5 record since 1820 CE also indicates a reduced ISM intensity. In addition, aerosol emissions may be another reason to cause weakened ISM. Because, aerosol emissions could result in a slowdown of the tropical meridional overturning circulation, cooler temperatures over Europe and Asia relative to the ambient oceans, and a corresponding weakening of the ISM circulation (Bollasina et al., 2011; Cowan and Cai, 2011).

(2) The rationale for why the authors think that their stacked record reflects regional changes in the monsoon is absent – the signals from each location appear coherent, but it is not shown that they are actually coherent. There’s a wide range in correlation coefficients between sites in Table 2, where the lowest correlation coefficients suggest that sampling at Manali only explains _5% of the variance observed at Bhutan. Thus, while we find the possibility that these sites record a regional-scale signal to be exciting, the rationale for combining all of these datasets for a regional interpretation should be explained in more detail. Additionally, the authors hint that the relationship between sites may not be stationary (pg 5, L18-21), as they note decadal-scale changes are often not observed coherently through their stacked record. The analysis would benefit from exploring potential reasons for why this might be the case - are there other potential explanations than

variations in the ISM?

Answer: The rationale for combing five tree ring oxygen isotope chronologies in monsoon area is that: tree ring oxygen isotopes in five sites show significant correlations with summer precipitation/PDSI, and summer climate in five sampling areas are controlled by Indian summer monsoon, so combining five oxygen isotope chronologies should be helpful to obtain monsoon-related information. The significant correlations between regional tree ring oxygen isotope chronology and all Indian monsoon/Indian summer monsoon Index/grid summer precipitation indicated that regional tree ring oxygen isotope chronology can reflect Indian summer monsoon changes. Given long distances (around 1400 km) between Manali and Buthan, correlation coefficient ($r=0.23$, $p<0.001$) is not bad. On the decadal-scale changes between different tree ring oxygen isotope chronologies, we discussed on it in another paper (Sano et al., under review). In addition, this is not the main topic of this paper.

We added the paragraph on the rationale for combing five tree ring oxygen isotope chronologies in monsoon area. Please see the following paragraph.

3.1 Tree ring $\delta^{18}O$ variations in the southern Himalaya and a regional tree ring $\delta^{18}O$ record

The oxygen isotopes of four individuals of *Abies spectabilis* in Ganesh (GE, central Nepal) and three individuals of *Cedrus deodara* in Jageshwar (JG, northern India) were measured for the interval from 1801-2000 CE and 1643-2008 CE, respectively. Individual tree ring $\delta^{18}O$ time series from four cores from central Nepal are shown in Figure 2a. The mean values of the $\delta^{18}O$ time series from 224c, 233b, 235b, and 226a are 23.09‰, 22.66‰, 21.87‰, and 22.94‰, respectively, from 1901-2000 CE; the standard deviations are 1.22‰, 1.27‰, 1.12‰, and 1.42‰, respectively. The inter-tree differences in $\delta^{18}O$ values are small. The $\delta^{18}O$ values of the four cores exhibit peaks in 1813. The mean inter-series correlations (Rbar) among the cores range from 0.56-0.78 (Figure 2c), based on a 50-year window over the interval from 1801-2000 CE.

Three tree ring $\delta^{18}O$ time series from northern India (JG) are shown in Figure 3a. The mean values of the $\delta^{18}O$ time series from 101c, 102c, and 103a are 30.11‰, 29.7‰ and 29.47‰, respectively, over the interval from 1694-2008 CE; the standard deviations are 1.49‰, 1.62‰ and 1.53‰, respectively. Three tree ring $\delta^{18}O$ time series in JG exhibit a consistent pattern of variations. The mean inter-series correlations (Rbar) among the cores range from 0.61-0.78

(Figure 3c), based on a 50-year window over the interval from 1641-2008 CE.

In northern Indian sub-continent, three long-term tree ring $\delta^{18}O$ chronologies from northwest India, eastern Nepal and Bhutan have been built up in previous studies (Sano et al., 2011; Sano et al., 2013; Sano et al., submitted, Figure 4). Two tree ring $\delta^{18}O$ chronologies in this study and three tree ring $\delta^{18}O$ chronologies in previous studies located in monsoonal area (Figure 1). Three tree ring $\delta^{18}O$ chronologies in northwest India, eastern Nepal and Bhutan were controlled by monsoon season rainfall or PDSI (Sano et al., 2011; Sano et al., 2013; Sano et al., submitted), and the two new tree ring $\delta^{18}O$ records obtained in the present study (JG and Ganesh) are negatively correlated with June-September PDSI in northern India. In addition, the five tree ring $\delta^{18}O$ records for the Himalaya region are significantly correlated each other during the common period (Table 2). These results indicate that five tree ring $\delta^{18}O$ records reflect a common controlling factor that may be related to regional climate. Therefore, we combined two tree ring $\delta^{18}O$ records in this study with three previously published tree ring $\delta^{18}O$ chronologies to construct a regional tree ring $\delta^{18}O$ record. The five $\delta^{18}O$ records were individually normalized over the interval from 1801-2000 CE, and then averaged to produce a regional Himalayan $\delta^{18}O$ record (H5 $\delta^{18}O$ record) for the entire interval (Figure 4f). Only one chronology (JG) spans an interval prior to 1742 CE, and therefore we focus on the interval from 1743-2008 CE in this study.

(3) The authors draw conclusions that may not be supported by their time series analysis methods. A section describing the spectral analysis methods, software, etc. that were used should be added to the methods section so that their results could be replicated by other researchers. Additionally, it is not clear how the authors determined the significance levels plotted in Figure 7 – this should be explained. A few additional comments/questions regarding the time series analysis are provided below: The conclusion that their record captures centennial-scale variability requires more justification considering their record is only 350 years long. They claim significant spectral power at 160 and 350 year intervals (Fig 7) – though the 350 year peak is the secular trend in their 350 year dataset, and the 160 year cycle may also not be significant-more details about how significance levels are determined should be provided. It was not clear why a 31-year moving correlation was used in figure 9 – could you expand on this choice?

Answer: Thank you for helpful suggestion. We have added the related sentence in Section 2.3 Meteorological data and climate analyses. We checked the codes that were used to calculate the Power Spectra based on the multi-taper method in previous manuscript. The calculation of the confidence level in low frequency have some problems. We recalculated power spectra based on the multi-taper method using the Software "kSpectra Toolkit"(v3.4). The results show that H5 regional tree ring $\delta^{18}O$ record contains several high-frequency periodicities (4 and 5 years), as well as lower frequency periodicities (~133 years) (New Figure 7).

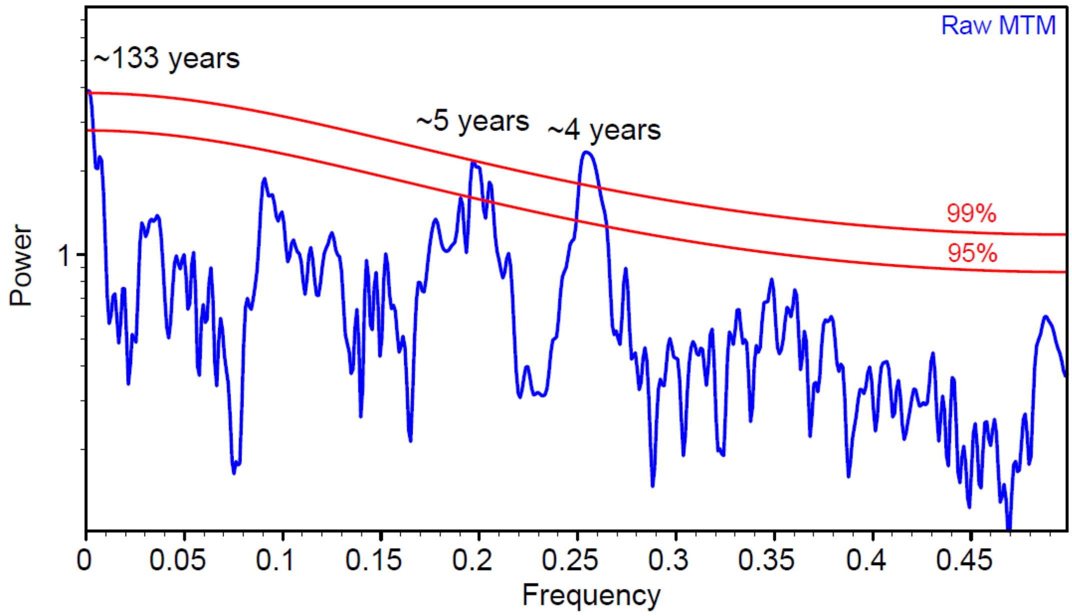


Figure Caption: Figure 7: Multi-taper power spectra for the H5 regional tree ring $\delta^{18}O$ record.

3.3 Interannual variability of the ISM inferred from the regional tree ring $\delta^{18}O$ record

The results of spectral analysis using the multi-taper method (Mann and Lees, 1996) indicates that the H5 regional tree ring $\delta^{18}O$ record contains several high-frequency quasi-periodicities (4 and 5 years), as well as lower frequency periodicities (~133 years) at a confidence level greater than 99% (Figure 7).

Maybe our explanation on 31-year moving correlation is not so clear. ENSO-Monsoon teleconnection is a nonstationary process. We need to evaluate the relationship between ENSO and monsoon. Because ENSO has the strongest power in wave length or cycles 2-7 yr, 31-year or 21-year window moving correlation between ENSO and precipitation were used to evaluate the stability of relationship between ENSO and climate. 31-year and 21-year window can cover the main cycles (2-7 years) of ENSO. For example, Camberlin et al., (2004, Climate Dynamics) used 31-year moving correlations between NINO3 SST and seasonal rainfall anomalies over a few regions to see ENSO/rainfall teleconnections. 21-year moving window correlation analysis between ENSO and climate was used to investigate the relationship between ENSO and East Asian winter monsoon/ precipitation and flood pulse in the Mekong River Basin (Kim et al., 2016; Räsänen and Kummu, 2013)

Camberlin P, Chauvin F, Douville H, et al. Simulated ENSO-tropical rainfall teleconnections in present-day and under enhanced greenhouse gases conditions. Climate Dynamics, 2004, 23(6):641-657.

Kim J W, An S I, Jun S Y, et al. ENSO and East Asian winter monsoon relationship modulation associated with the anomalous northwest Pacific anticyclone. Climate Dynamics, 2016:1-23.

Räsänen T A, Kummu M. Spatiotemporal influences of ENSO on precipitation and flood pulse in the Mekong River Basin. Journal of Hydrology, 2013, 476(1):154-168.

(4) Writing is imprecise and organization needs improvement. We have provided a few of the more pressing examples to help guide revisions:

- The methods section requires substantial additions. First, the time series analysis methods used need to be described in an additional subsection, and in enough detail that other researchers could recreate the analysis. Second, many of the paragraphs in the results start with a description of how an analysis was done - these should be moved to the methods section.

Answer: Thank you for helpful suggestions. We have revised this part according to your suggestions. Please see the revised part.

2.3 Climate analyses and Statistical Analysis

In the northern Indian subcontinent, the monsoon season is from June to September. The summer monsoon season supplies 78% and 83% of the annual precipitation for Kathmandu and New Delhi, respectively. The Indian monsoon index (IMI) (Wang et al., 2001), the intensity of monsoon circulation (Webster and Yang, 1992) and All India Rainfall (AIR, obtained from the Indian Institute of Tropical Meteorology , Pune, India) were selected as proxies for the Indian summer monsoon in order to investigate the relationship between tree ring cellulose $\delta^{18}O$ variations and the monsoon. In addition, we used the Royal Netherlands Meteorological Institute Climate Explorer (http://www.knmi.nl/) to determine spatial correlations between tree-ring cellulose $\delta^{18}O$, precipitation (GPCC V7) and sea-surface temperature (SST) values obtained from the National Climatic Data Center v4 data set. Temperature reconstructions for the Indian Ocean (Tierney et al., 2015) and the Tibetan Plateau (Cook et al., 2013; Shi et al., 2015; Wang et al., 2015), spanning the last 400 years, were used to obtain a record of the history of land-ocean thermal contrast. "kSpectra Toolkit"(v3.4) was employed to calculate power spectrum of the regional tree ring oxygen isotope chronology. The 95% (±1.96σ) confidence limits for each chronology and the regional chronology were calculated to show the uncertainty of each chronology and the regional chronology, respectively (except for the tree-ring chronology from Hulma, western Nepal, because the chronology was produced by pooling method, and therefore the uncertainty of this chronology was not able to show).

- The introduction brings up several relevant factors about the ISM without relating them directly to this study. This section would be more impactful if it were better focused on what is known about how these factors influence the ISM rather than just providing a list. This addition would help clarify how your results improve our understanding of the ISM.

Answer: Thank you for helpful suggestions. We have revised this part according to your suggestions. Please see the revised Introduction.

1 Introduction

The Indian summer monsoon (ISM) delivers a large amount of summer precipitation to the Indian continent, and thus has a major influence on economic activity and society in this densely-populated region (Webster et al., 1998). Current research on the ISM is mainly concerned with the study of inter-annual and inter-decadal variations, using meteorological data and climate models. El Niño-Southern Oscillation (ENSO) has great influences on ISM at inter-annual time scales, and El Niño events (Warm phase of ENSO) usually produced ISM failure (Kumar et al., 1999; Kumar et al., 2006; Webster et al., 1998). North Atlantic Sea surface temperature (SST) affected ISM by modulating tropospheric temperature over Eurasia (Goswami et al., 2006; Kripalani et al., 2007). Climate model experiments indicate that there is a significant increase in mean ISM precipitation of 8% under the doubling atmospheric carbon dioxide concentration scenario (Kripalani et al., 2007) and human-influenced aerosol emissions mainly resulted in observed precipitation decrease during the second half of the 20th century (Bollasina and Ramaswamy, 2011). A good understanding of mechanisms driving ISM change on different time scales could help to predict possible changes of ISM in the future. However, the observed meteorological records are too short to assess centennial changes in ISM. Therefore, long-term proxy records of ISM are needed.

The abundance of *Globigerina bulloides* in marine sediment cores from the Arabian Sea indicated a trend of increasing ISM strength during the last 400 years (Anderson et al., 2002). However, oxygen isotopes in tree-rings and ice cores from the Tibetan Plateau revealed a weakening trend ISM since 1840 or 1860 (Duan et al., 2004; Grießinger et al., 2016; Liu et al., 2014; Wernicke et al., 2015). Monsoon precipitation in northwestern India showed a significant decreasing trend during the period of 1866-2006 (Bhutiyani et al., 2010). In addition, a stalagmite oxygen isotope record from northern India indicated that the ISM experienced a 70-year pattern of variation over the last 200 years, with no clear trend (Sinha et al., 2015). Since there are spatial differences in the patterns of climate change in monsoonal areas (Sinha et al., 2011), geological records with a wide distribution are needed. In addition, the climate proxies used should be closely related to the ISM and the records need to be well-replicated and accurately dated.

Available tree ring records are widely distributed in the Indian monsoon region (Yadav et al., 2011). The climate of the southern Himalayas is dominated by changes in the Indian summer monsoon, and is therefore the region is well suited to the study of Indian monsoon variations. The oxygen isotopic composition ($\delta^{18}O$) of tree rings is mainly controlled by the $\delta^{18}O$ of precipitation and by relative humidity (Ramesh et al., 1985; Roden et al., 2000), and both are affected by the Indian summer monsoon (Vuille et al., 2005). Compared with tree ring width data, tree ring $\delta^{18}O$ records are more suited to retrieving low-frequency climate signals, and therefore they have the ability to record the Indian summer monsoon (Gagen et al., 2011; Sano et al., 2011; Sano et al., 2013). In addition, tree ring $\delta^{18}O$ is considered as a promising proxy for next phase of Past global changes (PAGES) 2k network not only for hydroclimate reconstruction in Asia but also for data-model comparison to understand the mechanisms of climate variability at decadal to centennial timescales.

PAGES launched 2k network that produced regional and global temperature and precipitation syntheses based on multi-proxy and multi-record to get a better understanding of regional and global climate change. ISM affected the large area of Indian continent, and a local record may not be fully representative of changes in the ISM. Therefore, we produced regional syntheses based on several tree ring $\delta^{18}O$ records from the ISM region. Two new records from northern India and central Nepal were obtained in this study, and were combined with three previously published records from northwest India, western Nepal and Bhutan (Sano et al., 2011; Sano et al., 2013; Sano et al., submitted). The data were integrated in order to produce a regional tree ring $\delta^{18}O$ record which was used to reconstruct the history of the ISM during the last few hundred years, and to investigate its possible driving mechanisms on various time scales.

- The discussion section analyzing why there may be a weakening monsoonal circulation over last few hundred years requires a more in-depth analysis. The presented tree ring records cannot answer this question, and the question diverges from the main focus of the paper. The land-sea contrast mechanism described is potentially interesting, but the authors need to be more descriptive about: (a) how well do we know there has been a change in the land-sea temperature contrast? (b) are there other potential explanations, given the long list of factors influencing the ISM the authors list in the introduction?

Answer: We have discussed possible reasons to result in the weakening Indian summer monsoon. Sun activity and atmospheric CO2 content were not responsible for the reduction of ISM. Decreased land-sea temperature contrast may be the main reason, based on the fact that low-frequency variations in our regional tree-ring chronology are well correlated with those in the land-sea contrast data. In addition, aerosol emissions may be another reason to cause weakened ISM. Please see the revised part.

3.4 Centennial variability of the ISM inferred from the regional tree ring $\delta^{18}O$ record

There are also significant centennial-scale variations in the H5 record (Figure 7), which were extracted using a 100-year low-pass filter (Figure 10c, red line). The record exhibits a decreasing trend from 1743 to 1820 CE and an increasing trend since 1820 CE, which indicates a weakening trend of the ISM during the interval from 1820-2000 CE. A reduction in the monsoon precipitation/relative humidity of the ISM in the last 200 years is also evident in other areas influenced by the ISM. Maar lake sediments in Myanmar exhibit a decreasing trend of monsoonal rainfall since 1840 CE (Sun et al., 2016); a tree ring $\delta^{18}O$ record from southeast Asia exhibits a drying trend since 1800 CE (Xu et al., 2013a); a stalagmite $\delta^{18}O$ record from southwest China reveals an overall decreasing trend in monsoon precipitation since 1760 CE (Tan et al., 2016); and in southwest China, tree ring $\delta^{18}O$ and maar lake records indicate reduced monsoon precipitation/relative humidity/cloud cover since 1840 or 1860 CE (Chu et al., 2011; Grießinger et al., 2016; Liu et al., 2014; Wernicke et al., 2015; Xu et al., 2012). Monsoon precipitation in northwestern India shows a significant decreasing trend during the period of 1866-2006 (Bhutiyani et al., 2010).

However, in contrast, marine sediment records from the Western and Southeastern Arabian Sea exhibit an increasing trend of ISM strength over the last four centuries (Anderson et al., 2002; Chauhan et al., 2010). In addition, a recent study indicated that the contrasting trends in the ISM during the last several hundred years observed in geological records resulted from the different behavior of the Bay of Bengal branch and Arabian Sea branch of the ISM (Tan et al., 2016). However, the tree ring $\delta^{18}O$ record in northwest India, influenced by the Arabian Sea branch of the ISM, exhibits a drying trend since 1950 CE (Sano et al., submitted), which does not support the idea of a strengthening ISM (Anderson et al., 2002). Moreover, there are no calibrated radiocarbon dates for the last 300 years for the two records from the Arabian Sea (Anderson et al., 2002a; Chauhan et al., 2010). We suggest that further high-resolution and well-dated ISM records from western India are needed to improve our understanding of the behavior of the ISM. Although reconstructed All India monsoon rainfall does not show a significant decreasing trend during the period of 1813-2005 (Sontakke et al., 2008), the data from only four stations extend back to 1826 CE and four longest stations locate in central or southern India. Monsoon season drying trend in northern India revealed by H5 regional tree ring $\delta^{18}O$ record may indicate that inland areas appear to be particularly sensitive to the weakening of monsoon circulation.

The H5 record suggests a decreasing trend of ISM strength, which is supported by most of the other well-dated and high-resolution ISM records in ISM margin areas. A previous study has indicated that solar irradiance has a significant influence on the ISM on multi-decadal to centennial timescales, and that reduced solar output is correlated with weaker ISM winds (Gupta et al., 2005). However, solar irradiance has increased since 1810-1820 CE (Bard et al., 2000; Lean et al., 1995) and therefore it cannot be the main reason for the weaker ISM since 1820 CE. Atmospheric CO_2 content is another forcing factor for the ISM, with higher atmospheric CO_2 content resulting in a stronger ISM (Kripalani et al., 2007; Meehl and Washington, 1993). Thus, the increased atmospheric CO_2 content during the last 200 years is unlikely to be the reason for the weakened ISM.

Several studies show that increased Indian Ocean SSTs caused a reduction in ISM rainfall (Fan et al., 2009; Naidu et al., 2009; Sun et al., 2016). The Indian Ocean SST has increased since 1840-1860 CE (Tierney et al., 2015; Wilson et al., 2006), which supports this explanation.

Although the SST of the Indian Ocean significantly affects the ISM, the land-sea thermal contrast is also an important influencing factor (Roxy et al., 2015). In particular, heating anomalies over the Tibetan Plateau have a significant influence on the ISM via their effect on the atmospheric temperature gradient between the Tibetan Plateau and the tropical Indian Ocean (Fu and Fletcher, 1985; Sun et al., 2010). The history of land-sea thermal contrasts is reconstructed based on temperature differences between the Tibetan Plateau and the Indian Ocean (Figure 10a), and centennial variations in this record are shown in Figure 10b. Three reconstructed land-sea thermal contrasts showed a decreasing trend since 1800 CE and 1820 CE (Figure 10b), and the H5 record exhibits a similar pattern of changes on a centennial scale (Figure 10c). The decreasing land-sea thermal contrast since 1800 and 1820 CE has resulted in a weaker ISM, and the increasing trend of the H5 record since 1820 CE also indicates a reduced ISM intensity. In addition, aerosol emissions may be another reason to cause weakened ISM. Because, aerosol emissions could result in a slowdown of the tropical meridional overturning circulation, cooler temperatures over Europe and Asia relative to the ambient oceans, and a corresponding weakening of the ISM circulation (Bollasina et al., 2011; Cowan and Cai, 2011).

Following the SPATIAL laboratory group discussion, Rich Fiorella compiled this short comment based on input from Gabe Bowen, Rose Smith, Annie Putman, Crystal Tulley-Cordova, Chao Ma, Zhongyin Cai, Yusuf Jameel, Brenden Fischer-Femal, and Sagarika Banerjee.